Resource Security Strategies and Their Environmental and Economic Implications: A Case Study of Copper Production in Japan

Motoori, Ran; McLellan, Benjamin; Chapman, Andrew; Tezuka, Tetsuo

energies

MDPI

Article

Resource Security Strategies and Their Environmental and Economic Implications: A Case Study of Copper Production in Japan

Ran Motoori [1,*], Benjamin McLellan [1], Andrew Chapman [2] and Tetsuo Tezuka [1]

[1] Graduate School of Energy Science, Kyoto University, Kyoto 6068501, Japan
[2] International Institute for Carbon Neutral Energy Research, Kyushu University, Fukuoka 8190395, Japan
* Correspondence: motoori.ran.45m@st.kyoto-u.ac.jp

Received: 25 June 2019; Accepted: 3 August 2019; Published: 6 August 2019

Abstract: Japan is a nation which is highly dependent on the import of raw materials to supply its manufacturing industry, notable among them copper. When extracting copper from ore, a large amount of energy is required, typically leading to high levels of CO_2 emissions due to the fossil fuel-dominated energy mix. Moreover, maintaining security of raw material supply is difficult if imports are the only source utilized. This study examines the environmental and economic impacts of domestic mineral production from the recycling of end-of-life products and deep ocean mining as strategies to reduce CO_2 emissions and enhance security of raw material supplies. The results indicate that under the given assumptions, recycling, which is typically considered to be less CO_2 intensive, produces higher domestic emissions than current copper processing, although across the whole supply chain shows promise. As the total quantity of domestic resources from deep ocean ores are much smaller than the potential from recycling, it is possible that recycling could become a mainstream supply alternative, while deep ocean mining is more likely to be a niche supply source. Implications of a progressively aging society and flow-on impacts for the recycling sector are discussed.

Keywords: resource security; domestic mineral production; input-output analysis; environmental assessment; transition

1. Introduction

As nations undergo a low-carbon energy transition, including large-scale electrification and a shift toward a more efficient transportation system, the need for mineral raw materials (ore and concentrates), some of which are critical, are expected to increase [1,2]. Japan is a nation which is highly dependent on the import of such raw materials for industry, and the need to conserve limited resources and maintaining resource security are considered important to the Japanese public [3]. Japan is completely dependent on imports of raw materials such as for ferrous and non-ferrous metal ores and concentrates (e.g., iron, copper, lead and zinc), which makes it vulnerable to potential global supply disruptions. Such disruptions may occur for various political, economic and environmental reasons. Recent discourse around resource security has been focused on critical materials, essential for industry, civil life and military applications for which alternative materials are not available and which use minerals whose probability of supply restriction is elevated or, in some cases, whose environmental implications of supply are high [4]. "Critical materials" can be broadly defined as relating to materials that fulfil an important (or vital) role in society and for which there is a high possibility of supply restriction, which could lead to higher prices (economic scarcity) or physical unavailability (physical scarcity). A variety of factors are typically included in the evaluation of "criticality", which includes factors of economic importance or reliance (vulnerability to supply restriction, including the number of people using, the importance to economic sectors and the potential for substitution) and supply risk (factors that affect this might include the level of monopolization of supply chains, environmental intensity of production and governance in producing countries). Taking copper for example, it is vital to some applications such as electric wire but can be substituted with aluminum with some loss of performance; at the same time, the global production of copper ore is quite diversified, giving a potentially lower supply risk. Due to increasing demand and potential for lagging supply, ore grade decline in terrestrial mines and potential subsequent cost increases per ton of metal, it may face both economic and physical scarcity.

The specific definition of a critical material differs from nation to nation, depending on the applied evaluation criteria although materials such as rare earth elements (REE) and Platinum group metals (PGM) are common among materials considered as critical in most nations. In Japan, as a country that is almost entirely dependent on imports of raw materials, apart from the concept of "criticality", other metals are considered "strategic" due to their economic importance (regardless of the likelihood of global supply disruptions which is included in criticality), including copper, lead, nickel and zinc [5–7]. This reasoning underpins their consideration as strategic materials in Japan.

Resource importing countries have severe limits on their ability to exert control over political, economic or environmental issues which are occurring in resource exporting countries. Cognizant of this limitation and, as metals play an important role in achieving a low-carbon society [8], many import-reliant countries have seen the need to develop a resource acquisition or resource security strategy. Application of these strategic metals to renewable energy includes, for example, photovoltaic panel requiring copper, indium, gallium and selenium and wind turbines requiring nickel, molybdenum, neodymium and boron as functional materials [8]. As renewable energy installation increases, battery demand will also likely increase. Lithium-ion batteries are one key storage option in renewable energy societies, and these also include potentially critical minerals such as cobalt and lithium [8]. In order to improve low levels of raw-material self-sufficiency, each country needs to decide their own approach. For example, the USA drew up the Critical Materials Strategy [7], the EU developed the Critical raw materials for the EU [5], while the Japanese government outlined their strategy in the Strategic Energy Plan [9]. This plan includes a raft of measures, such as, supply diversification, recycling of end-of-life products and research and development for extraction from unestablished or alternative materials [6]. Of these measures, all are dependent on other nations, except for research and development and domestic recycling of end-of-life products. In order to ameliorate this issue, domestic mineral production needs to be considered alongside domestic recycling in order to achieve resource security, critical to the low-carbon energy transition. The circular economy is one tightly-linked concept to maximize resource efficiency and minimize waste production, within the context of sustainable economic and social development [10]. Promoting recycling is one of the key components of the circular economy, as well as a key strategy for critical material resource security.

This research focuses on the effects of domestic copper production and recycling in Japan. Copper is selected from among the group of critical materials as it has many applications and demand is expected to increase due to expanded renewable energy deployment such as CIGS photovoltaic panel and CIS (copper (C), indium (I) and selenium (S)) photovoltaic panel [11]. Recently, the United States published a federal strategy, which focuses on the improvement of critical mineral supply by: Identifying new sources of critical minerals, enhancing activity at all levels of the supply chain, seeking to stimulate private sector investment and growth of domestic downstream value-added processing and manufacturing, ensuring that miners, producers, and land managers have access to the most advanced mapping data; and outlining a path to streamline leasing and permitting processes in a safe and environmentally responsible manner [12]. Resource acquisition options for an import-reliant country include (1) on-land mining, (2) imports of raw materials, (3) recycling, and (4) unconventional resource exploration. In the context of Japan, because of its lack of on-land mines, option (1) is unlikely. In terms of improving resource security, option (2) does not relieve the vulnerability to export restrictions by exporting countries. Lacking known deposits on land or near shore, development of domestic primary production is focused on ore production by means of deep ocean seafloor massive sulfide (SMS) mining. Thus, recycling and deep sea mining (which is a subset of option (4)) are the options to be discussed in this study.

This study aims to assess the constraints of energy, material, economic and labor under domestic mineral production.

2. Background and Literature Review

In recent history, mineral resource security policy in Japan has been highly dependent on the acquisition of mining rights in resource exporting countries [13]. For example, Japan Oil, Gas and Metals National Corporation (JOGMEC), the organization in charge of contributing to a stable supply of petroleum, natural gas and mineral products, undertakes joint exploration for copper and gold in Australia. Through this project JOGMEC expects to contribute toward resource security in Japan [14]. Although Japan's defined self-sufficiency rate reflects the acquisition of mining rights in resource exporting countries (so that the apparent self-sufficiency rate of base metals in Japan is about 50%) [9], for most metals there is no domestic mining, and there is no policy promoting the extraction of minerals in Japan.

With regards to copper in Japan, 100% of mineral concentrate is imported, and the annual production of copper in Japan in 2017 was 1488 kt, split between the end uses of wire (64%), brass (35%), and casting (1%) [15]. The recycling rate for 2017 was reported as 32% [15]. The recycling rate reflects the percentage of copper produced utilizing copper scrap. In-process scrap, which is scrap generated during wire or brass production, is utilized at the rate of almost 100% and the wire and brass industry also utilizes end-of-life product scrap, which is generated from waste copper products, for production [16]. Scrap produced in Japan was distributed to the wire, brass, copper smelting and export industries [16]. Wire and brass industries use scrap so that they can reduce material input costs [16]. The smelting industry uses scrap to productively utilize the excess heat created by the converting reaction in converter furnaces [17]. Copper smelting and export industries currently process lower grade scrap, whereas high grade scrap was recycled in the wire and brass sectors [16]. China has consistently been a major importer of Japan's scrap—particularly scrap which required labor inputs in order to be economically recycled (such as plastic-coated cables). However, scrap imports, including not only copper scrap but also various kinds of metal scrap, slag and plastic imports were banned by China in 2018, in order to protect the environment [18]. This outcome means that Japan will need to process lower grade scrap domestically or find an alternative processing destination.

In the EU, following China's scrap import ban, waste paper and plastics which were anticipated to be shipped to China were shifted to other countries such as Vietnam, Thailand and India [19]. Copper scrap export data after China's policy change is not yet available, however it is expected that overflows of copper scrap will be sent to third parties.

Lack of an export market for scrap, with a shift to processing within Japan could potentially create new industry activities such as end-of-life product collection.

Considering the dual issues of resource security and environmental protection in both scrap producing and importing nations, recycling more copper within Japan could help ameliorate resource security and environmental issues.

One issue that arises from a strategy of greater domestic recycling is the downgrading of copper scrap due to impurities. Currently, the wire and brass industries both seek to prevent impurities and maintain a high-quality product, cognizant of the fact that no dedicated recycled copper refineries exist in Japan. According to the Metal Economic Research Institute Japan (MERIJ), two-thirds of brass makers maintain their own standards for scrap metals, 80% of which are stricter than the current Japanese Industrial Standard (JIS) [16]. MERIJ has also identified the issue of the increasing difficulty faced in securing employees for the typical techniques required to ensure high-quality copper scrap that are highly dependent on labor [16].

In addition to scrap recycling and direct imports, an alternative supply source for raw materials in Japan is provided by extraction of unconventional ores which lie on the seafloor using deep ocean mining. Deep ocean resources with Japan's exclusive economic zone (EEZ) such as SMS, manganese nodules and rare earth rich deep-sea muds have been widely studied [20]. The key reason for this is Japan's lack of commercial terrestrial domestic mining, which makes importing the only way for Japan to supply its mineral concentrate needs. Under this constraint, the current supply system is vulnerable to supply disruptions from external parties and this may engender significant economic damage to the manufacturing industry if key mineral inputs are affected. Although modern-day deep ocean mining technologies and the current deposit levels are not yet economically competitive with land-based mining, utilizing these resources in the future may ease the potential for untoward impacts should supply disruptions occur. The strength of deep ocean mining is its lower waste footprint. Land-based mining requires land clearing and, removal of overburden before extraction of the valuable ore. On the other hand, deep ocean mining does not need to remove much overburden for extraction. When deep ocean resources are extracted, waste rock is expected to be significantly lower than terrestrial mining [21]. Of course, there are many uncertainties around deep ocean mining, across all fronts—technical, environmental, economic and social. Notably, most studies consider the biodiversity and direct ecosystem impacts of deep ocean mining, which are difficult to compare adequately with land-based mining because of the lack of environmental baselines as well as the lack of commercial deep ocean mines as precedents. Thus, these aspects—which may be negative for deep ocean mining—are left out of the present examination.

One of Japan's well-studied potential deep ocean ore bodies lies approximately 110 km offshore from Okinawa Island [22]. It is reported that this deposit has 0.4% of copper (3000 kt), 1.4% of lead (10,000 kt), 5.8% of zinc (43,000 kt), 1.5g/t of gold (11 t), and 95.6 g/t of silver (1 kt) [23]. Although the total quantity of copper in this deposit is not large considering Japan's annual copper demand is approximately 1500 kt [15], combined production with other metals such as zinc, lead, gold and silver could contribute positively toward overall national resource security.

This study aims to contribute to the debate surrounding resource security for nations reliant on raw material imports, and to specifically investigate recycling approaches, deep ocean mining, and a combination of the two. This approach is applicable to not only copper but also other non-ferrous minerals. Copper has been chosen as a case study because of following reasons. Lead, which is used in applications such as automobile batteries or large-scale batteries, is already recycled effectively, giving only marginal potential for improvement. On the other hand, zinc is typically used in alloys, or for additives in galvanization or paints or as sacrificial anodes, which can be considered dissipative uses. Generally speaking, it is difficult to recover zinc metal by itself, but it is recovered in the steel recycling process. Unlike these metals, copper is used as the main material in products, in relatively pure form, and there is still room for improvement in recycling rates. Copper is therefore chosen as a case study, although this approach could be applied to these and other metals that are found in unconventional ore deposits.

3. Methodology

This study focuses on domestic mineral production in Japan as primary ore via deep ocean mining or as secondary material from recycling. In order to elucidate the energy, material, economic and labor flows, input-output analysis and material flow analysis will be employed in this study. The system boundary considered in this study is shown in Figure 1. Copper production is dependent on (A) the import of raw material, and domestic mineral production including: (B) Deep ocean mining and (C) end-of-life product recycling.

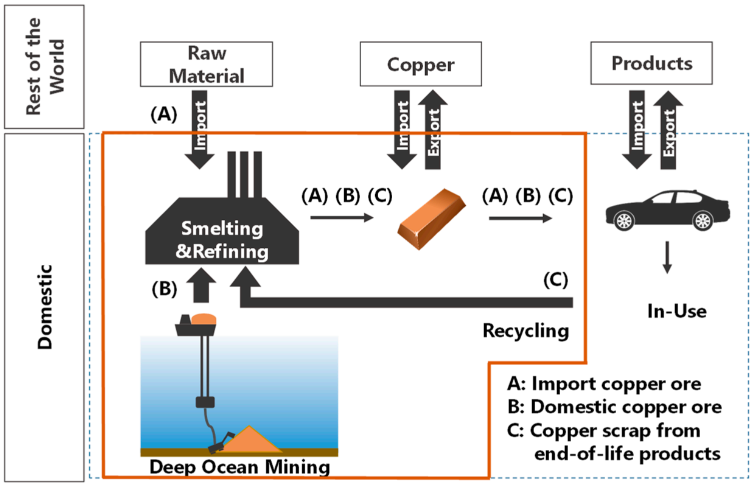

Figure 1. Copper material flow of domestic copper production system (bold box indicates the system boundary).

Detailed processes are shown in Figure 2. Due to the fact that both imported ores and domestic ores are sulfides, it is possible to utilize the same smelting facilities. As each production process will produce refined copper, the focus of this study, there are considered to be no quality issues that could prevent certain sectors from utilizing copper. The scope of this study is specific to the copper production process, while further processing for manufacturing electrical wire, brass or automobiles is not considered.

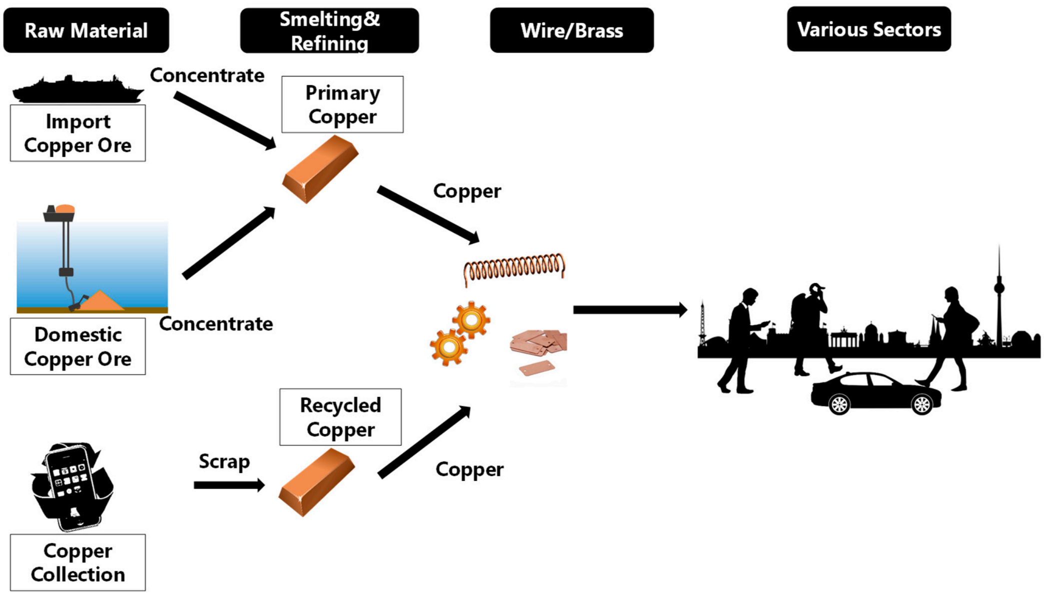

Figure 2. Material flows between sectors related to copper production in this study (boxes indicate sectors in the I-O table).

3.1. *Input-Output Analysis*

This study analyzes domestic mineral production in Japan utilizing the Japanese Input-Output (I-O) Tables from 2011, the latest version available at the time of writing, in which copper is differentiated from other minerals [24]. The I-O table is a statistical table showing inter-industry transactions of goods and services conducted in the domestic economy for a certain period (usually one year) in matrix form. This table has been prepared for the purpose of understanding the economic structure of a single region (country, prefecture or city level, although international I-O tables also exist). It is also possible to analyze economic ripple (multiplier) effects by using this table. Economic ripple effect can be defined as new economic production which is triggered to meet new demand. Currently, there are no industries dedicated specifically to deep ocean mining, secondary copper smelting/refining and end-of-life product collection in Japan. Deep ocean resource exploration requires mining and concentration processes which do not currently exist in Japan. Within the I-O table, the recycling sector is reflected, however this is not specific to copper recycling. Should domestic mineral production become mainstream, such sectors would likely emerge in the I-O table. However, it is impossible to investigate these sectors when employing the I-O table in its current form, and for this reason the Japanese 2011 I-O table has been extended in order to add these emerging sectors.

Although I-O analysis is widely used, we will present a brief description of the methods here. Figure 3 shows a conceptualized I-O table. Each row of the I-O table indicates the output of inter-industry transactions, while the columns of the I-O table show the inputs to each industry on a monetary basis. Intermediate demand sectors, which are sectors producing each good or service, perform production activities through the purchase of raw materials, services or energy and applying capital and labor. The final demand sector, which covers consumption, exports and imports, is mainly a buyer of consumer and capital goods as finished products. The intermediate input sector is a supplier of goods and services as intermediate goods. Each supply industry supplies goods and services to demand industries. The gross value added sector consists of a factor cost for production (such as capital and labor). Essentially, the subtotal of final demand and the subtotal of gross added value are balanced. The I-O table is balanced by Equations (1) and (2).

$$[x + F + Ex - Im = Y] \tag{1}$$

$$[x + V = Y] \tag{2}$$

x: Intermediate input, F: Domestic final demand, Ex: Export, Im: Import, Y: Domestic production, V: Value added.

Demand side / Supply site		Intermediate demand				Final demand			Domestic production
		Industry 1	Industry 2	...	Industry n	Domestic final demand	Export	Import	
Intermediate input	Industry 1	$x_{1,1}$	$x_{1,2}$	...	$x_{1,n}$	F_1	Ex_1	Im_1	Y_1
	Industry 2	$x_{2,1}$	$x_{2,2}$	...	$x_{2,n}$	F_2	Ex_2	Im_2	Y_2
	...	...	...	...	...	...	...	...	...
	Industry n	$x_{n,1}$	$x_{n,2}$	...	$x_{n,n}$	F_n	Ex_n	Im_n	Y_n
Gross value added		V_1	V_2	...	V_n				
Domestic production		Y_1	Y_2	...	Y_n				

Figure 3. General conceptualized input-output table.

The input coefficient matrix, which is explained by Equation (3) and also known as the technology coefficient matrix, represents the raw material inputs required to produce 1 unit of the desired product. By utilizing the inverse matrix of the input coefficient matrix, the economic ripple effect can be estimated using Equation (4). The inverse matrix in Equation (4), $(I - A)^{-1}$, is known as the Leontief inverse matrix.

$$a_{ij} = x_{ij}/Y_j \tag{3}$$

$$\text{Economic ripple effect} = (I - A)^{-1}\Delta \tag{4}$$

$a_{i,j}$: input coefficient, $x_{i,j}$: intermediate input in sector ij, Y_j: Domestic production in sector j, A: Input coefficient matrix, I: Identity matrix.

As noted above, since the Japanese I-O table combines various mineral ore industries into one sector, copper ore should be separated from this sector to consider domestic mineral production. Also, the recycling sector does not clearly delineate copper flows. Thus, this study modifies the conventional I-O table to suit to domestic mineral production by using the procedures detailed below.

3.1.1. Copper Ore

The copper ore sector, which was separated from the mineral sector, is then separated into two sectors; imported copper ore and domestic copper ore. Both sectors only produce ore for the primary copper sector. The input structure (which is the materials and services for producing copper expressed in the columns of the I-O table), of domestic copper ore is approximated using the Chilean copper production structure [25].

3.1.2. Copper Collection

The end-of-life copper collection sector was added to the extended I-O table. This sector collects end-of-life copper products such as electronic home appliances or metal containing products, disassembles and sorts them and produces materials to be recycled by copper smelters, the ferrous sector and plastic sector. Note that the I-O table only allows a single output from a single sector, so, it is assumed that this sector produces raw materials only for the secondary copper sector. The input structure of this sector is approximated using life cycle assessment (LCA) data from a previous study [26].

3.1.3. Copper Recycling

When large amounts of scrap become the main raw material for copper production, primary copper smelters cannot be utilized due to technical limitations. This limitation necessitates the use of a furnace for recycling, which can process scrap materials [17]. To highlight the flow of recycled copper, this sector is newly added to the extended I-O table. The output structure of this sector is identical to primary copper smelting.

End-of-life products are collected and sorted into individual grades and provided to suitable sectors for modern day copper recycling. This means that copper scrap collected from end-users is not always recycled as copper and could be used for wire or brass production. This type of recycling, often called cascading may cause quality issues due to impurities. To prevent downgrading, the recycled copper sector and copper collection sectors are independent of each other, which means that collected copper scrap considered in this study is processed only to high-quality copper. Table 1 highlights the sectors and options considered in the extended I-O table.

Table 1. Sectors added to the extended I-O table.

Added Sector	Code	Notes
Import copper ore	CONV	Import copper concentrate; does not include concentrating processes in Japan.
Domestic copper ore	DOM	From mining to concentration. Does not include the distance from concentration site to smelter.
Recycled copper	REC	Separated from conventional primary copper processing. Does not use flash smelting.
Copper collection	REC	Collecting, disassembling and sorting of end-of-life products. Distance from collecting point to sorting point is included.

3.2. *Assumptions*

In addition to the augmentation of the I-O table, the following assumptions are made for this study.

3.2.1. Copper Production

This study assumes that copper production in any scenario is set at 1500 kt, equal to copper production at 2017 in Japan [15]. The gross domestic product (GDP), which is the total of the value added by all sectors, is also set to the same value as the 2011 I-O table in order to highlight the difference in final demand distribution among sectors, rather than overall GDP change.

3.2.2. End-of-Life Product Recycling

We assume that the copper collecting sector recovers end-of-life products from consumers, dismantles, sorts and separates them, and provides secondary materials for secondary copper production, iron and steel and plastic sectors. Here, it is assumed that there is a collection point of end-of-life products in the city, requiring consumers to bring end-of-life products for collectors to gather them. The "recovery" of the end-of-life copper collecting sector is transported from these collecting points to the copper recycling smelters [26].

As recycling progresses, the value of production in the recycled copper production sector and the copper recovery sector will increase and the intermediate input and import value of the imported copper ore sector will decrease. The copper recovery sector is assumed to be an industry that requires labor. Wages for this labor were substituted using values from the similarly structured waste treatment sector [27].

3.2.3. Extended I-O Table

Imported copper ore, domestic copper ore, primary copper, recycled copper, and the copper collecting sector were newly added to the 2011 I-O table. Copper production and GDP are assumed to remain constant at 2011 levels. When estimating final demand and domestic production for the progressing recycle rate, the input factor and ratio of the final demand sector to domestic production for each industry are used.

It was also assumed that the wage rates for estimating the labor force costs are the same as in the 2011 I-O table. In addition, wages are set in accordance with the employment table of the I-O Table.

This study applies both a bottom-up and top-down approach to estimating the input coefficients for extended industries. Figure 4 details the methodology used to extend the I-O table for this study. For example, for deep ocean mining (a non-existent industry in Japan) the input coefficient is substituted for that of land-based mining in Chile (a top-down estimate). On the other hand, the input coefficients for industries related to recycling are estimated through a bottom-up estimate approach, using LCA data [26]. LCA data is mass-based, and for the purposes of this study, these data were converted to a monetary basis utilizing the value and quantity table attached to the I-O table.

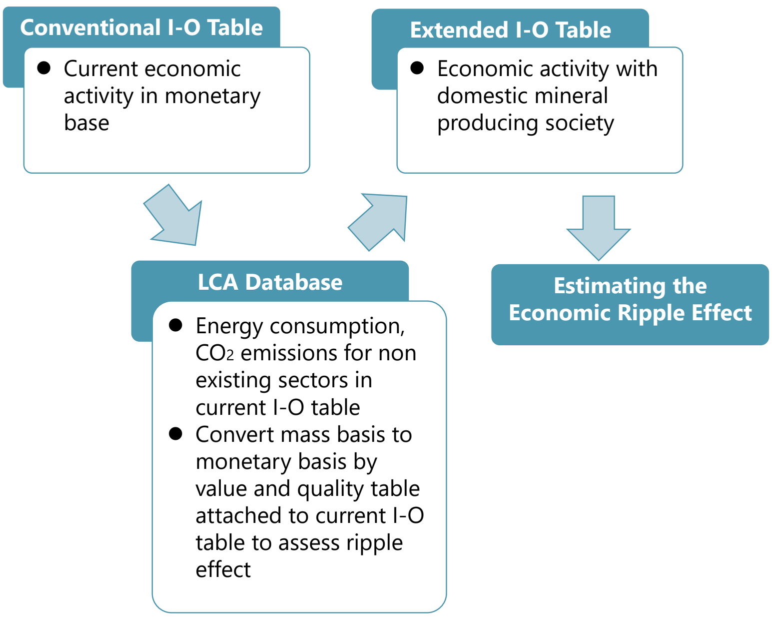

Figure 4. Methodology to extend the I-O table.

3.2.4. SMS Ore Production

As SMS deposits are polymetallic, deep ocean mining is not specifically targeted toward copper recovery and will result in multiple minerals being recovered—in fact, in many cases copper is more likely to be a coproduct. For example, the ore body considered here consists of copper, lead, zinc, gold and silver. The ore grade has been estimated at 0.4% (copper), 1.4% (lead) and 5.8% (zinc) [22]. To estimate environmental impact factors of SMS ore production, allocation by weight is usually adopted. Previous research revealed that multiple mineral production from SMS ore reduces energy consumption, CO_2 emissions and waste disposal amounts (due to their allocations to each material extracted) when compared to the production of copper ore alone [10]. This study applies the assumption that deep ocean mining will produce various minerals in addition to the target metal of copper for the estimation of environmental impacts.

According to current estimates, SMS reserves of ore are not sufficient to cover Japan's production [12], however there are large uncertainties as to the available resources, so this study assumes for the purpose of analysis that there is no limitation on this resource and that SMS ore can meet the demand.

3.2.5. Energy Consumption and CO_2 Emissions

The recycling of end-of-life products is considered to reduce energy consumption and CO_2 emissions when compared with processing ore, since recycling does not require an oxidization process. Additionally, since it is possible to utilize waste plastics as a reducing agent and energy source, we estimate that utilizing end-of-life products will assist in reducing CO_2.

Deep ocean mining is also able to reduce energy consumption and CO_2 emissions due to shorter material transportation distances. Mining, concentrating and transportation are invisible processes for resource importing countries since these processes are conducted only in resource exporting nations. Domestic mineral production by Japan may also have the flow on effect of reducing CO_2 emissions in resource exporting countries, although this is not considered in this study. To estimate Japanese CO_2 emission impacts, existing LCA data are used [26].

3.2.6. Labor

The I-O table contains supplemental information regarding labor and employment. An example portion of the employment table is shown in Figure 5. The inducement of employment by demand increase is estimated utilizing this data, focusing on all employed persons, including the employer as well as self-employed persons and family workers.

	Sector 1	Sector 2	Sector 3	⋯	Sector n
Employee	l_{11}	l_{12}	l_{13}	⋯	l_{1n}
Self-employed	l_{21}	l_{22}	l_{23}	⋯	l_{2n}
Family worker	l_{31}	l_{32}	l_{33}	⋯	l_{3n}
⋮	⋮	⋮	⋮		⋮
Domestic production	X_1	X_2	X_3	⋯	X_n

Employment Table

Figure 5. Employment table.

The employment factor is estimated using Equation (5). As shown in Equation (6), by transforming employment factors to a diagonal matrix and by multiplying the domestic production of each sector, employment inducement due to 1 unit of demand increase is estimated. The scale of the inducement can be estimated by dividing the average of the sum of all industries.

$$p_j = L_j / X_j \tag{5}$$

p_j: employment coefficient L_j: employed person in sector j X_j: Domestic production in sector j.

$$Employment\ Inducement = \hat{L} \cdot (I - A)^{-1} \tag{6}$$

$\hat{L}$: $diagonal\ matrix\ of\ p_j$.

Annual income per person can also be estimated by the employment table, as the table includes average incomes along with the number of employed persons. Since copper collection does not exist as an activity within the current I-O table, incomes from the similar waste collection industry are substituted here.

4. Results

The results are expressed in three parts beginning with I-O analysis, final energy consumption and CO_2 emissions, followed by labor impacts.

4.1. I-O Analysis

I-O analysis reveals industries that will be affected by domestic mineral production. This study considers two extremes; 100% SMS production and 100% recycling. I-O analysis reveals that in a recycling society, 1 unit increase of final demand of recycled copper engenders 1.43 overall units. Table 2 shows the top five industries that will be affected.

Table 2. Economic ripple effect in recycled copper sector.

Industry	Ripple Effect
Recycled Copper	1.00
Copper Collection	0.26
Transportation	0.06
Service Industry	0.03
Electricity	0.02

On the other hand, an increase in deep ocean mining on final demand engenders a 1.75 unit increase, with the top 5 industries shown at Table 3.

Table 3. Economic ripple effect in domestic copper ore sector.

Industry	Ripple Effect
Domestic Copper Ore (Deep Ocean Mining)	1.14
Service Industry	0.19
Electricity	0.09
Mining (minerals and quarrying except copper ore)	0.09
Transportation	0.06

The estimated ripple effect in either case is smaller than for other industries, since the average ripple effect of all industries is 2.40. However, observing these impacts, deep ocean mining will relatively increase the output (on a monetary basis) of other industries more than copper recycling alone, as demand for copper increases.

4.2. Final Energy Consumption and CO_2 Emissions

Final energy consumption is estimated based on I-O and material flow analysis. In each process, multiple minerals are produced and this study allocates energy consumption and CO_2 emissions by the ratio of mass of final products.

Figure 6 indicates domestic energy consumption for the copper recycling scenario. A recycling rate of up to 10% only requires conventional copper smelting due to the relatively low capacity. For rates of 20% and above both conventional and recycled copper processing are required. As the recycling rate increases, the amount of energy required for transportation (collecting end-of-life products) increases rapidly.

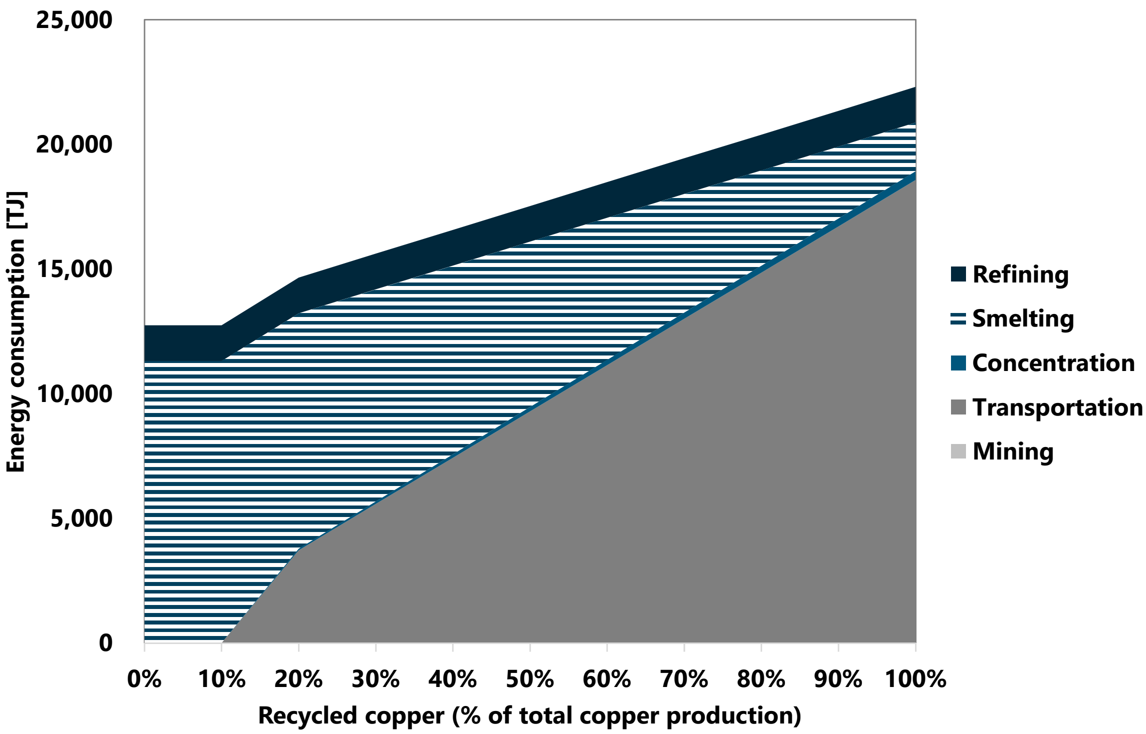

Figure 6. Final energy consumption in a recycling society.

Figure 7 shows energy consumption required for deep ocean mining. Although the reserves of deep ocean ore are very small relative to the total copper demand in Japan, this limitation is deliberately ignored here. Basically, the deep ocean mining scenario can be considered to be using conventional smelting and refining processes with added domestic mining and ore concentration. Thus, the energy required for mining and concentration processes increases as the supply provided by deep ocean ores increases.

According to this result, domestic mineral production will increase overall energy consumption. In the case of recycling, energy for smelting succeeds in reducing energy consumption due to the utilization of waste plastics and the absence of an oxidization process. However, transportation of end-of-life products consumes the most energy across all processes. In the case of deep ocean mining, mining and concentration processes are added to the current copper production system. The mining processes require more energy than concentration processes. Note that the current import-based system estimate does not consider mining, transportation and concentration processes because these are all currently conducted abroad. As our estimates only encompass the domestic impacts, actual total energy consumption will be greater than our estimate due to international energy consumption.

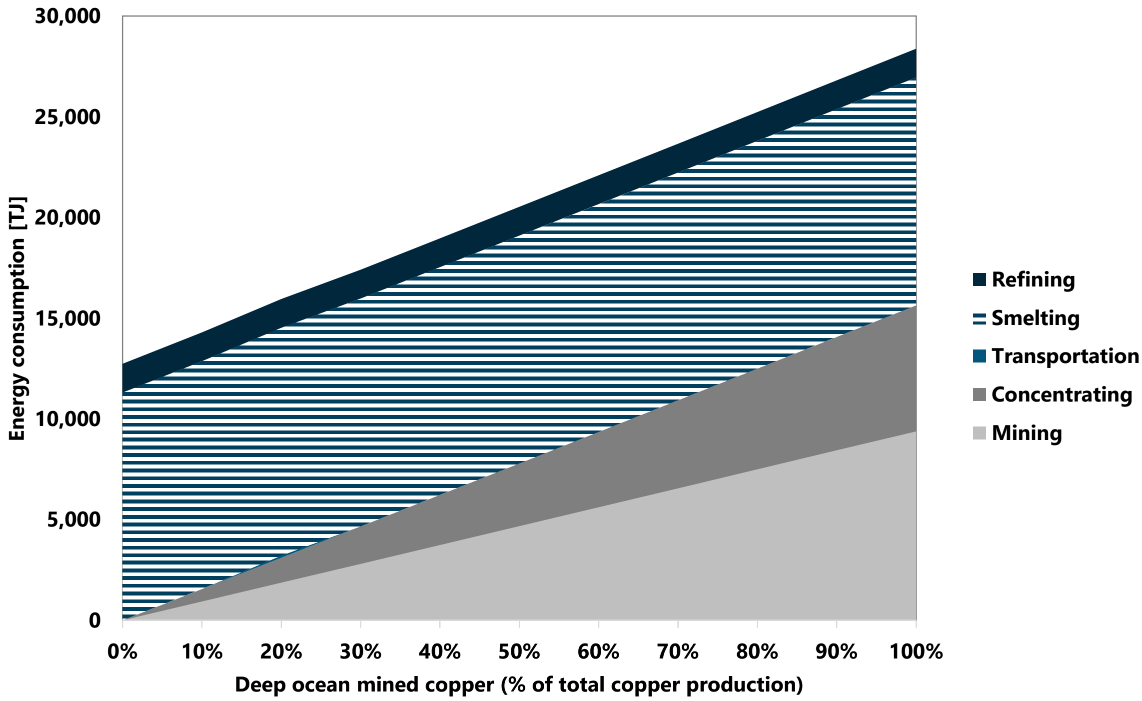

Figure 7. Final energy consumption for deep ocean mining.

Contrarily, CO_2 emissions in domestic mineral production may be less than for conventional copper processing. Figure 8 shows CO_2 emissions, incorporating those from overseas. It can be seen that deep ocean mining will contribute additional CO_2 emissions when compared with current copper production, however, considering the available reserves it is likely not a feasible method to supply Japan's copper ore needs solely from SMS deposits. It is more likely that domestic mineral production will utilize recycling, leading to a reduction in CO_2 emissions from copper production. Note that since environmental impact allocation is based on the mass balance, CO_2 emissions in mining and concentration of deep ocean mining process are smaller than those in conventional processes. A value-based allocation may change these outcomes.

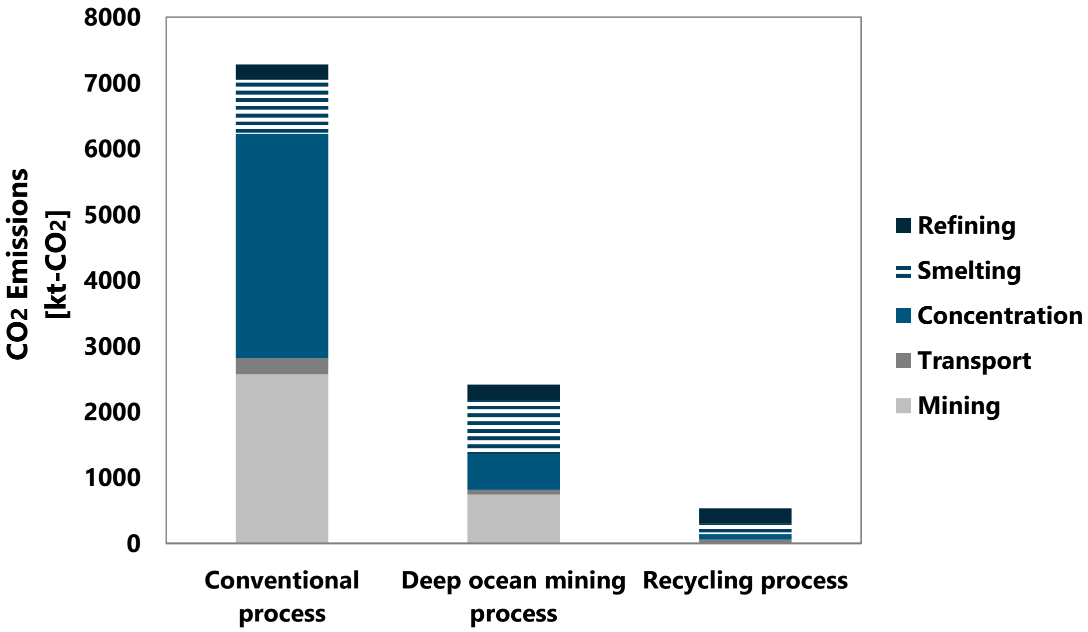

Figure 8. CO_2 emissions in copper production.

In addition, Japan's population is forecast to continue to decrease into the future. According to the National Institute of Population and Social Security Research, by 2055, the population in Japan will reduce to roughly 100 million people, approximately 80% of the current population [28].

Table 4 shows the population change observed and forecasted in Japan [28,29]. Following the assumption that copper consumption per person will remain constant, Japan's overall requirements for copper will decrease. Thus, by 2055 we anticipate that environmental impacts will be limited to those shown at an 80% DOM or recycling level in Figures 6 and 7, although alternatively exports could increase to take-up additional copper production. This study assumed that copper consumption per capita and GDP is constant. It has been shown that copper consumption is strongly correlated to GDP per capita [30]. Following the assumption that copper consumption per capita is stable, it is more important to maintain the GDP per capita when considering an aging society, which could lead to a decline in copper consumption commensurate with population decrease.

Table 4. Population change in Japan and copper consumption.

Year	Age Group 0–14 [Thousand People] [28]	Age Group 15–64 [Thousand People] [28]	Age Group 65–74 [Thousand People] [28]	Age Group More That 75 [Thousand People] [28]	Copper Consumption [kt] [28]
1995	19,400	87,000	12,000	7800	1300
2015	15,900	77,300	17,500	16,300	1300
2035	12,500	64,900	15,200	22,600	1200
2055	10,100	50,300	12,600	24,500	1000

4.3. Labor

Based on the I-O analysis, employment induced by recycling will make it the third largest sector next to textiles and construction. This indicates that the demand increase for recycled copper will lead to a larger labor demand.

When the final demand increased by 1 unit (1 million yen), 0.17 people are required as labor. Comparing to other industries under the same assumptions, recycling is the industry which requires labor force the most.

Average annual income per person in the recycling industry is estimated to be about three million yen, the second lowest income level in Japan. This industry may struggle to attract employees under these conditions

5. Discussion

In terms of economic ripple effect, it is estimated that copper ore production via deep ocean SMS mining will give a larger effect than that yielded by recycling alone. Demand increase for recycled copper leads to a commensurate demand increase for copper collection. It is also estimated that this demand increase for copper collection will also lead to a larger labor demand. It is unclear from the methodology applied in this study as to whether the recycling sector will increase the overall number of employees or simply extend the working hours of the current employee pool. This is one of the limitations of I-O analysis and an issue faced by Japan as a whole. Another limitation of the I-O table is the limitation of bottom-up estimation of input coefficients. As this study mainly employed bottom-up analysis based on LCA data, it does not consider industries which do not appear in the LCA for the given technologies (e.g., service industry). In that sense, energy consumption or CO_2 emissions can be considered as a conservative estimate. Regarding LCA, allocation in this study employed mass balance allocation assuming multiple mineral recovery the likelihood may be very low of its actual occurrence, but when only copper is recovered, the environmental impacts of deep ocean mining are much larger than the conventional process. Figure 9 shows the comparison of CO_2 emissions when only copper is recovered. CO_2 emissions from the recycling process are smaller than the conventional process though, unlike multiple mineral recovery, domestic emissions will become larger than what they are today. In the case of deep ocean mining, it will not be able to reduce CO_2 emissions across the entire copper supply chain.

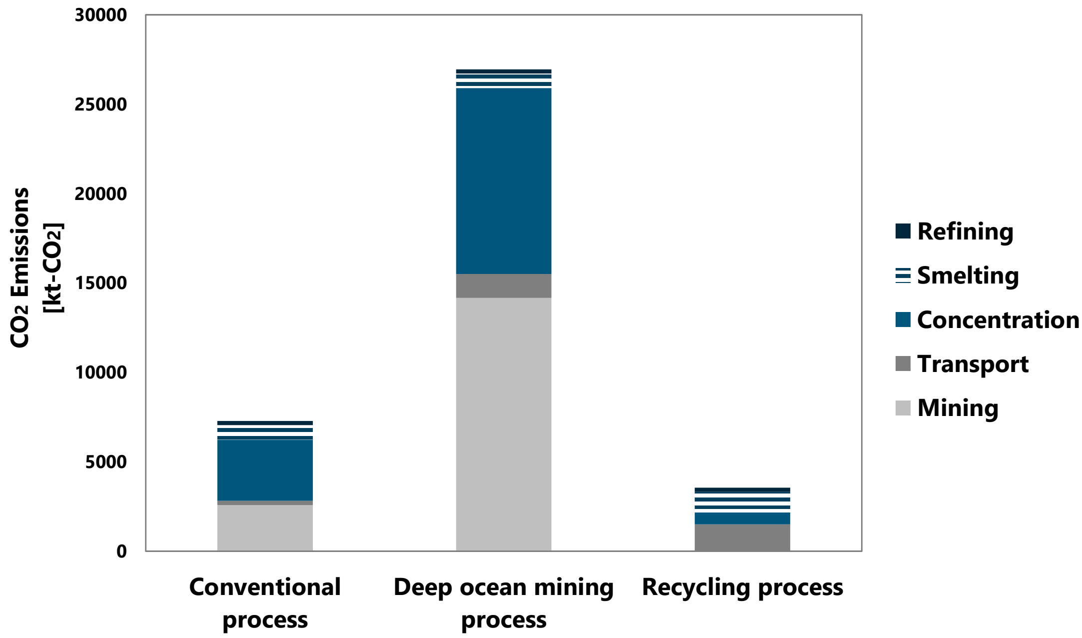

Figure 9. CO_2 emissions under the assumption that all emissions for deep ocean mining and recycling are allocated to copper.

As mentioned in the introduction, up until the end of 2018, Japan had been exporting lower grade copper scrap to China [31]. In the context of Japanese resource security, processing scrap in Japan could contribute to building a more stable supply chain and build a measure of resilience against inopportune external events including political, economic or environmental restrictions. A measure of independence from importing raw materials will result in resource security improvements. Also, according to the results of this study, a national approach to recycling or deep ocean mining, or a combination of the two can also contribute toward decreasing CO_2 emissions across the entire copper supply chain. Although some positive aspects are identified, we also find that the available working population may be a limitation for Japan's copper recycling capacity. In order to address these issues, we assessed three mitigatory measures, as follows.

Sensitivity Analysis

Process 1. Smelter Process End-of-Life Products Scraps

This study assumed that all scrap is dismantled and separated, and then processed in a smelting plant. Under this type of recycling regime, generally, high-quality separation is not required since impurities are treated at the smelting and refining process. Processed end-of-life copper scrap by smelters proposes that smelters disassemble end-of-life products and collect scrap by utilizing shredders and separation machinery. This type of recycling is expected to decrease energy requirements for concentration and labor when compared to the recycling option assessed in this study. The labor and energy needs of each facility is based on previous studies [32] and it is assumed that all pre-treatment processes such as crushing are conducted close to the smelting plant, so that energy for transportation is negligible.

Process 2. Producing Sector Processes Collected Waste

Since smelters play an important role in recycling in this study, it is assumed to be preferential to maintain smelters' profits under any future regime. One way to achieve this is to improve the recovery rate from scrap. Smelters' recycling process proposed that the smelter would be responsible for scrap collection, however, the mixture of materials will likely cause a lower recovery level of materials. Thus, in processed end-of-life products by producing sectors, producers of final products are made responsible for dismantling and sorting. This is achieved by producers installing mechanical dismantling facilities in their production factories. Metals and a certain amount of plastics will be provided to the recycled copper sector, with producers able to collect desirable materials. As the wire industry is able to reuse their end-of-life products, only scrap for brass production theoretically needs to be recycled. Generally, brass scrap contains about 60% copper. Copper demand for the brass industry was approximately 30% of total copper production in 2011 [15]. Thus, energy consumption for transportation is allocated at 60%, with smelting and refining at 30%. In this case zinc from brass scrap is also assumed to be recovered. Since this recycling process requires careful dismantling processes, the labor requirements are assumed to be the same as for the production stream. It is expected to improve the smelters' profit rate compared to the recycling process by smelters, but it may reduce overall profits due to a reduced quantity of available scrap. Moreover, this approach will increase system costs and energy for transportation. This approach also requires a large investment for producing industries, as it is assumed that the labor requirements for this process are the same amount as for the production process, i.e. securing the labor base is critical to its success. This type of recycling does not necessarily produce copper and may not increase the recycling rate according to the current Japanese definition [15].

Process 3. Local Recycling

The above two recycling process options both rely on hardware. However, this process encourages community level (including residential and commercial) recycling by consumers. This approach does not consider disassembling and sorting as full-time work. By consigning the disassembling and sorting process to consumers, the copper collection industry will not require large amounts of labor as is necessary for options (1) and (2). Finalizing scrap before the smelting process is a major function for the copper collection process within this process. According to the Ministry of Environment of Japan, copper accounts for 7% of end-of-life household electronic appliance materials after removing plastic and ferrous metals [33]. For this process, instead of hiring workers, the copper collection industry will provide incentives to consumers who separate their end-of-life products prior to recycling. Labor used for disassembling is not considered in the same way as options (1) and (2), but as a voluntary practice. Labor within this process only includes the workers in the copper finalizing processes. As we assume rapid aging in Japan, the retiring generations will likely play an important role in this proposed process. In addition, consumer driven recycling may provide non-traditional employment opportunities for those wishing to continue working past the retirement age. Table 5 illustrates a comparison among the three proposed mitigatory processes and the recycling of copper through traditional channels in Japan when 1 unit of final demand increase.

Table 5. Efficiency of processes proposed when compared with baseline copper recycling [corresponding to 1 unit change in copper recycling sector].

Process	Energy [GJ]	CO_2 Emissions [t-CO_2]	Labor [No. of People]
Process 1	+0.2	0	−0.02
Process 2	+0.5	0	+0.03
Process 3	−0.1	0	−0.02

Comparing these three process, we observe the existence of an energy-emissions-labor trade-off. Process 1 increase energy, however it is able to produce comparable amounts of copper with a relatively small labor force. Process 2 increase energy consumption and the estimated labor requirement the most, it may be impossible to realize under Japan's current demographic restrictions, i.e. an aging, shrinking society. Process 3 seems to be the ideal process approach with a moderate energy and emissions contribution and the smallest labor (actually hired) requirements of the three proposed approaches. Process 3 is unlikely to be realized unless consumers are willing to cooperate, as separating and sorting processes are dependent on consumers under this process. Note that CO_2 emissions in each process is less than 1 kg.

6. Conclusions

Japan is facing a number of challenges, among them, an aging shrinking population, and over-dependence on raw material imports from foreign nations. This study seeks to provide policy implications and recommendations for improving resource security in Japan, incorporating both recycling and indigenous deep ocean mining operations. Findings show that although deep ocean mining may have strong flow-on economic impacts, the overall quantity of copper extracted may not contribute strongly to Japan's resource security. On the other hand, I-O analysis of domestic copper production scenarios provides a new finding, that labor may be a constraint of realizing a recycling-centric society. Although producing copper by recycling eases environmental impacts, it requires significant manpower.

In order to overcome these shortcomings of individual resource security policies, this study provides three processes, complemented by economic, environmental and social analyses—considering employment, demographics and societal norms.

The analysis undertaken in this study enables a deeper understanding of the effect of demand increase for new industries under constant technological coefficients. However, I-O table-based analysis has some limitations. Since the I-O table is a snapshot of a single year, the effect of investment over the long-term is not recognized. A model to analyze the effect of longer-term investments, such as recycling plant construction which takes longer than a single I-O period will allow for the further development of this research

Author Contributions: Conceptualization, R.M. and B.M.; methodology, R.M.; software, R.M.; validation, R.M., B.M; formal analysis, R.M.; investigation, R.M.; resources, R.M.; data curation, R.M.; writing—original draft preparation, R.M.; writing—review and editing, A.C., B.M. and T.T.; visualization, R.M.; supervision, A.C., B.M. and T.T.;

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Watari, T.; McLellan, B.C.; Giurco, D.; Dominish, E.; Yamasue, E.; Nansai, K. Total material requirement for the global energy transition to 2050: A focus on transport and electricity. *Resour. Conserv. Recycl.* **2019**, *148*, 91–103. [CrossRef]
2. Månberger, A.; Stenqvist, B. Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development. *Energy Policy* **2018**, *119*, 226–241. [CrossRef]
3. Chapman, A.; Shigetomi, Y. Developing national frameworks for inclusive sustainable development incorporating lifestyle factor importance. *J. Clean. Prod.* **2018**, *200*, 39–47. [CrossRef]
4. National Research Council of the US. *Minerals, Critical Minerals, and the U.S. Economy*; National Academies Press: Washington, DC, USA, 2008; ISBN 978-0-309-11282-6.
5. European Commission. *Report on Critical Raw Materials for the EU, Report of the Ad Hoc Working Group on Defining Critical Raw Materials*; European Commission: Brussels, Belgium, 2014; p. 41.
6. Prime Minister's Office of Japan. *Shigen Kakuho Senryaku [Resource Securing Strategy]*; Prime Minister's Office of Japan: Tokyo, Japan, 2012; pp. 1–30.
7. U.S. Department of Energy. *Critical Materials Strategy*; U.S. Department of Energy: Washington, DC, USA, 2011; p. 191.
8. La Porta, D.; Hund, K.; McCormick, M.; Ningthoujam, J.; Drexhage, J. *The Growing Role of Minerals and Metals for a Low Carbon Future*; World Bank: Washington, DC, USA, 2017.
9. Government of Japan. *Strategic Energy Plan*; Government of Japan: Tokyo, Japan, 2018.

10. Hislop, H.; Hill, J. *Reinventing the Wheel: A Circular Economy for Resource Security*; Green Alliance: London, UK, 2011.
11. Elshkaki, A.; Graedel, T.E.; Ciacci, L.; Reck, B. Copper demand, supply, and associated energy use to 2050. *Glob. Environ. Chang.* **2016**, *39*, 305–315. [CrossRef]
12. U.S. Department of Commerce. *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals*; U.S. Department of Commerce: Washington, DC, USA, 2019; p. 51.
13. Hatayama, H.; Tahara, K. Evaluating the sufficiency of Japan's mineral resource entitlements for supply risk mitigation. *Resour. Policy* **2015**, *44*, 72–80. [CrossRef]
14. JOGMEC. Signed a Joint Copper and Gold Exploration Contract in Australia. Available online: http://www.jogmec.go.jp/news/release/news_06_000271.html (accessed on 18 June 2019). (In Japanese).
15. JOGMEC. *Kobutsu Shigen Materiaru Furo 2017 [Mineral Resources Material Flow 2017]*; JOGMEC: Tokyo, Japan, 2017; pp. 1–15.
16. MERIJ. *Do Oyobi Dogokin Risaikurugenryo No Genjo to Anteikakuho Katsuyo Eno Kadai [Current Situation of Copper and Copper Alloy Recycled Materials and the Challenges to Its Stability Ensured and Utilization]*; MERIJ: Tokyo, Japan, 2015.
17. Mark, E.S.; King, M.J.; Sole, K.C.; Davenport, W.G. *Extractive Metallurgy of Copper*, 5th ed.; Elsevier: Amsterdam, The Netherlands, 2011; ISBN 9780080967899.
18. Ministry of Ecology and Environment of the People's Republic of China. *Announcement on Adjusting "Catalogue of Imported Waste Management"*; Ministry of Ecology and Environment of the People's Republic of China: Beijing, China, 2018.
19. Eurostat Recycling—Secondary Material Price Indicator. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Recycling_%E2%80%93_secondary_material_price_indicator&oldid=422150 (accessed on 18 June 2019).
20. Masuda, N. Challenges toward the sea-floor massive sulfide mining with more advanced technologies. In Proceedings of the 2011 IEEE Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies, Tokyo, Japan, 5–8 April 2011; pp. 1–4.
21. Hein, J.R.; Mizell, K.; Koschinsky, A.; Conrad, T.A. Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. *Ore Geol. Rev.* **2013**, *51*, 1–14. [CrossRef]
22. Agency for Natural Resource and Energy of Japan. Kaitei Nessui Kosho Kaihatsu Keikaku Dai Ikki Saishu Hyoka Hokokusho [1st Term Final Evaluation Report of Deep Ocean Hydrothermal Ore Development Project]. Available online: https://www.jogmec.go.jp/content/300110684.pdf (accessed on 11 November 2018).
23. Agency for Natural Resource and Energy of Japan; JOGMEC. *Kaitei Nessui Kosho Kaihatsu Sogo Hyoka Hokokusho [Report of the Comprehensive Assessment]*; Agency for Natural Resource and Energy of Japan: Tokyo, Japan, 2018; p. 158.
24. Ministry of Internal Affairs and Communications of Japan. 2011 Input-Output Tables for Japan. Available online: http://www.soumu.go.jp/english/dgpp_ss/data/io/io11.htm (accessed on 16 June 2019).
25. OECD. Input-Output Tables in Chile. 2011. Available online: https://stats.oecd.org/Index.aspx?DataSetCode=IOTSI4_2018 (accessed on 6 June 2019).
26. Motoori, R.; McLellan, B.C.; Tezuka, T. Environmental Implications of Resource Security Strategies for Critical Minerals: A Case Study of Copper in Japan. *Minerals* **2018**, *8*, 558. [CrossRef]
27. Ministry of Internal Affairs and Communications. Employment Matrix. Available online: https://www.e-stat.go.jp/en/stat-search/files?page=1&layout=datalist&toukei=00200603&tstat=000001073129&cycle=0 (accessed on 11 July 2019).
28. National Institute of Population and Social Security Research. *Population Projections for Japan: 2016–2065*; National Institute of Population and Social Security Research: Tokyo, Japan, 2017; pp. 1–385.
29. Statistics Breau of Japan. *Japan Statistical Yearbook 2019*; Ministry of Internal Affairs and Communications Japan: Tokyo, Japan, 2018; p. 781.
30. Kishita, Y.; Inoue, Y.; Kobayashi, H.; Fukushige, S.; Umeda, Y. Feasibility Assessment of Sustainability Scenarios Based on the Estimation of Metal Demand (Case Analysis of Long-Term Energy Scenarios Focusing on the Risk of Copper Depletion). *Trans. Japan Soc. Mech. Eng. Ser. C* **2013**, *79*, 3221–3233. [CrossRef]
31. Ministry of Finance of Japan. Trade Statistics of Japan. Available online: http://www.customs.go.jp/toukei/info/index_e.htm (accessed on 16 June 2019).

32. Coelho, A.; De Brito, J. Economic viability analysis of a construction and demolition waste recycling plant in Portugal—Part I: Location, materials, technology and economic analysis. *J. Clean. Prod.* **2013**, *39*, 338–352. [CrossRef]
33. Ministry of Environment of Japan. Kogata Denki Denshi Kiki Ni Fukumareru Yuyo Kinzoku Ganyuryo [List of Metals Contained in Small Electrical and Electronic Equipment (Board, Parts, Material Composition)]. Available online: http://www.env.go.jp/council/former2013/03haiki/y0324-05b.html (accessed on 11 November 2018).